ENGR7005: Advanced Powertrain Engineering

Coursework

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Part 1

Introduction

In recent years, improving fuel economy and reducing the pollutant emissions has become a priority in the automotive industry. Addressing to the concerns, drive cycle is considered as an essential tool for assessing vehicle performance for a typical driving pattern in a controlled environment. A drive cycle consists of a sequence of driving behaviour defined in terms of vehicle speed with respect to time. Simulating the model for a given drive cycle enables to test and estimate vehicle performance. The use cases of drive cycle includes engine testing, driveline durability testing, estimation of fuel economy and pollutant emission and more.

The following report focuses on modelling and simulation of an Euro IV vehicle model for estimating fuel economy and emission levels for multiple legislative drive cycles and real-world drive cycles in order to identify the critical parameters affecting fuel efficiency and emissions level.

Drive Cycle development

In order to ensure that the performance measured accurately reflects driving conditions particular to that region, different legislative drive cycles have been developed and standardised for different regions. The development of a drive cycle requires taking into account variables such as environment, traffic conditions, driving style, distance, duration etc. The developed drive cycle represents the real driving behaviour in Oxford, which includes using both urban and highways. Speedometer app was used to measure the speed of the vehicle which collects data using GPS.

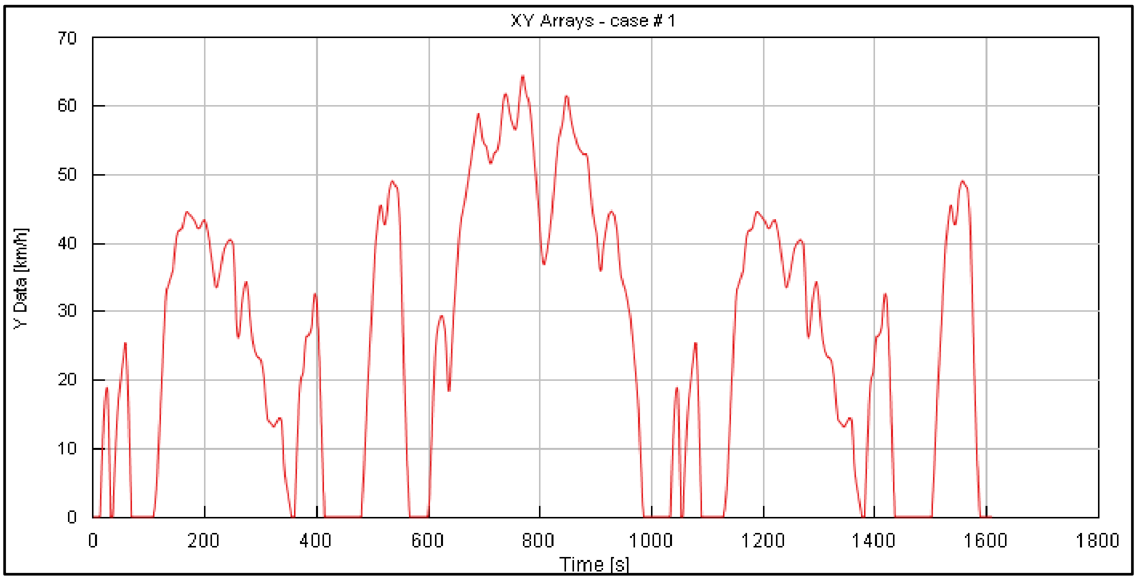

Figure 1 Speed profile for Real world driving (own drive cycle)

Model

The VW Lupo 1.4(100bhp) was used as reference Euro IV vehicle which was modelled and simulated in GT-Drive software. This numerical simulation method uses performance maps (steady-state engine performance maps and tailpipe-out emission maps) as look-up table for estimating the fuel efficiency and pollutant emissions as a function of engine speed and load.

The below listed are the key parameters modified, for modelling the vehicle.

Description		Values
Vehicle Body	Mass of the vehicle	945 Kg
	Frontal Area	$1.95\ m^2$
	Co-efficient of Drag	0.39
	Tire Rolling Radius	278.85mm
	Wheelbase	2.32
Differential	Final Drive Ratio	3.88
Transmission	Gear Ratio 1^{st} 2^{nd} 3^{rd} 4^{th} & 5^{th}	3.46, 2.10, 1.45, 1.10 & 0.89
Engine	Engine Displacement	1.4 litre
	Mechanical Output Map	BMEP Map
	Fuel Rate Map	Fuel Consumption Map
	Total Airflow Map	Air flow map
	Emission Maps	CO_2, CO, NOx & HC Map

Table 1 Model Parameters

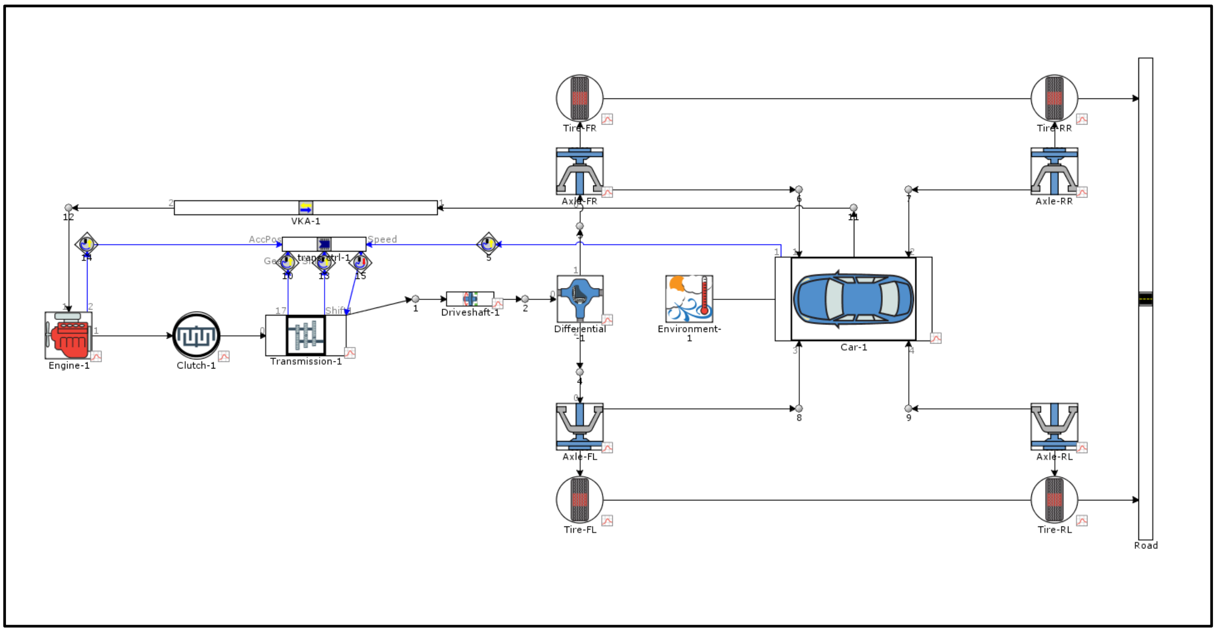

Figure 2 Model Architecture

The engine object is a map based model wherein maps contains the information about different engine parameters required to estimate the performance of the engine under different operating conditions. The vehicle Kinematic (VKA) object is used to impose the vehicle speed with respect to time by specifying the drive cycle. Whereas, the transmission control strategy was defined for the selection of subsequent gear based on the vehicle speed.

Validation

Validating the model with experimental results is a critical step in ensuring the accuracy and reliability of the model. As a part of validation, the developed model was simulated for NEDC drive cycle and the obtained fuel consumption and emission values were then compared with experimental test results. The data from (Samuel, et al., 2005) were used as reference for validation of the model as the parameters considered were for warmed-up engine, whereas the VCA results were obtained for cold start operating condition.

Parameter	Experimental Test Data (for NEDC)	Simulation Test Data (for NEDC)
Fuel Consumption (L/100 km)	7.1	7.12
Emission CO2 (g/km)	168	168.374
Emission CO (g/km)	0.238	0.155
Emission NOx (g/km)	0.014	0.0147
Emission HC (g/km)	0.061	0.012

Table 2 Comparison of simulation and experimental test results for validation of model

Since the simulation employs steady-state maps approach, some obtained results particularly for emissions are expected to slightly vary from the experimental results considering their sensitive behaviour and the hysteretic effects associated due to transient operation occurring during practical driving conditions. (Gao, et al., 2015) Thus, taking tolerance limitations into consideration the simulated model was validated.

Results and discussion

The considered drive cycles differed in terms of the driving pattern such as distance travelled, duration, maximum speed, acceleration-deceleration rate, braking, driving style like aggressive, passive or intermediate behaviour, so variations in the results were expected. It was verified that the simulation model followed the specified speed profile for the given cycle, so that the predicted results could be considered for comparison.

Table3 contains observations recorded to view the effect of changing drive patterns for each pollutant species and fuel economy of the model.

Part 1 Observation Table

	Unit	NEDC	FTP75_kph	US06	JPN10-15	WLTC	OwnDriveCycle
Total Distance Traveled	m	11013.194	17768.652	12887.582	4165.278	11427.667	15334.342
Average Gas Mileage	km/L	14.04359626047	14.335083750225	13.978158367215	11.979905868	14.459456518815	12.75729285369
Average Fuel Consumption	L/100 km	7.1207037	6.9759126	7.154039	8.347336	6.9159093	7.838677
Total Emissions: Co2	g	1854.3413	2926.2795	2135.5122	823.5115	1870.2505	2823.0198
Total Emissions: NOx	g	0.16252017	0.45298275	0.5484164	0.068771206	0.18104313	0.598408
Total Emissions: Co	g	1.7133055	2.8606536	27.805128	0.42408854	0.76929486	14.587305
Total Emissions: HC	g	0.13332966	0.23363115	0.3391088	0.053858787	0.09371564	0.26714256

Table 3 Comparison of Pollutant emission and fuel consumption for multiple drive cycle.

New Report Table 1

	Unit	NEDC	FTP75_kph	US06	JPN10-15	WLTC	OwnDriveCycle
Average Vehicle Speed	km/h	33.599575	34.134018	77.84445	22.719696	25.536686	28.8873
Maximum Vehicle Speed	km/h	120.0	91.2	129.23032	70.0	64.4	109.28972
Total Number of Gear Shifts		32.0	126.0	46.0	24.0	28.0	70.0
Average Vehicle Deceleration	m/s^2	-0.7885803	-0.5760641	-0.72847635	-0.6469181	-0.23721616	-0.33239922
Maximum Vehicle Deceleration	m/s^2	-1.3888888	-1.5	-3.084576	-0.8333333	-1.1111112	-4.116667
Average Vehicle Acceleration	m/s^2	0.59371233	0.5104543	0.6697685	0.5688937	0.22031498	0.45294282
Maximum Vehicle Acceleration	m/s^2	1.0416666	1.5	3.755136	0.7936508	0.8055556	3.5416667
Total Distance Traveled	km	11.013194	17.768652	12.887582	4.165278	11.427667	15.334342

Table 4 Comparison of driving behaviour parameters

Fuel Consumption

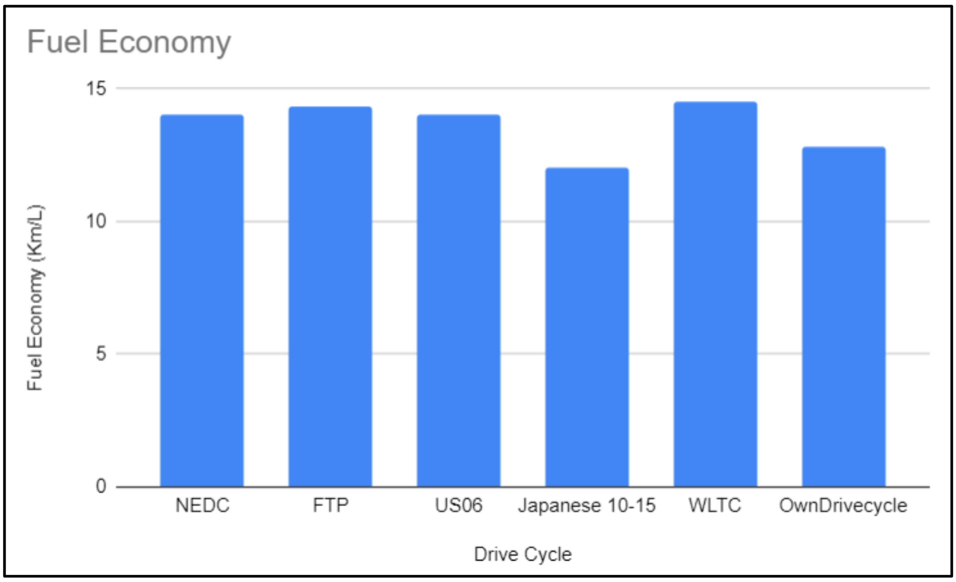

Figure 3 Comparison of fuel economy for considered drive cycle

Except for the Japanese10-15 & Real-world drive cycle, which exhibited considerable variation, the fuel consumption results for the simulated drive cycles were almost identical, with an average economy of 14.20 km/L (7.04L/100km). In comparison to other drive cycles, the two drive cycles had longer idle time, lower average speed, frequent gear shifts which has an influence for lower fuel economy.

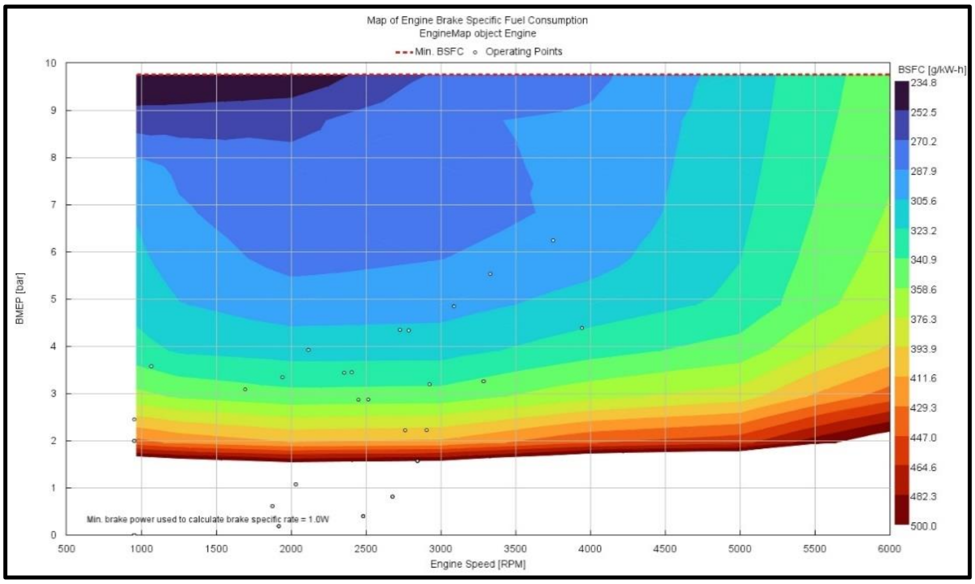

Figure 4 Engine Brake Specific Fuel Consumption for NEDC

The Brake Specific Fuel Consumption (BSFC) map allows to estimate the fuel efficiency of an engine by taking into consideration the fuel rate for per unit of generated power for a given operating condition. Using the BSFC Map the ideal operating range can be identified to improve the overall fuel economy. Engine load is an important factor which affects the fuel economy, with lower load the engine efficiency decreases.

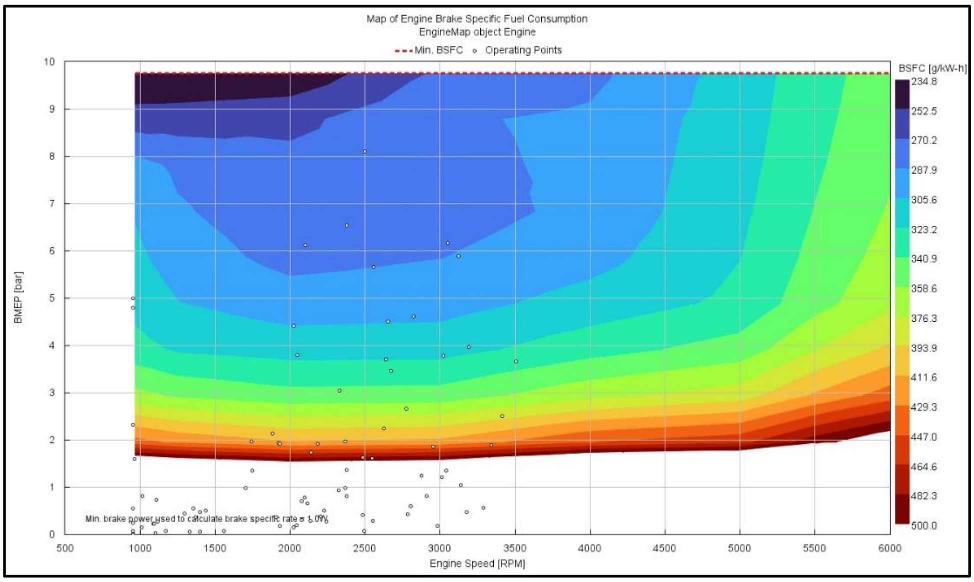

Figure 5 Engine Brake Specific Fuel Consumption for Own drive cycle

In comparison with the NEDC drive cycle which has comparatively better fuel economy the BSFC map of real-world drive cycle indicates that majority of the engines operating point is outside the ideal operating range resulting in higher fuel consumption for generating unit power.

Emission levels

The total emission factor considered are in terms of g/km. Since the total emission of CO2 directly depend on total fuel consumption, a higher emission is observed in Jpn10-15 and Real-world drive cycle. The US06 being an aggressive drive cycle, includes high speed driving for long duration resulting in higher emission CO pollutant. Whereas it can be concluded that the emission of NOx and HC depends upon multiple parameters of driving behaviour such as the operating range, rapid acceleration and deceleration, frequent halts, distance travelled and more.

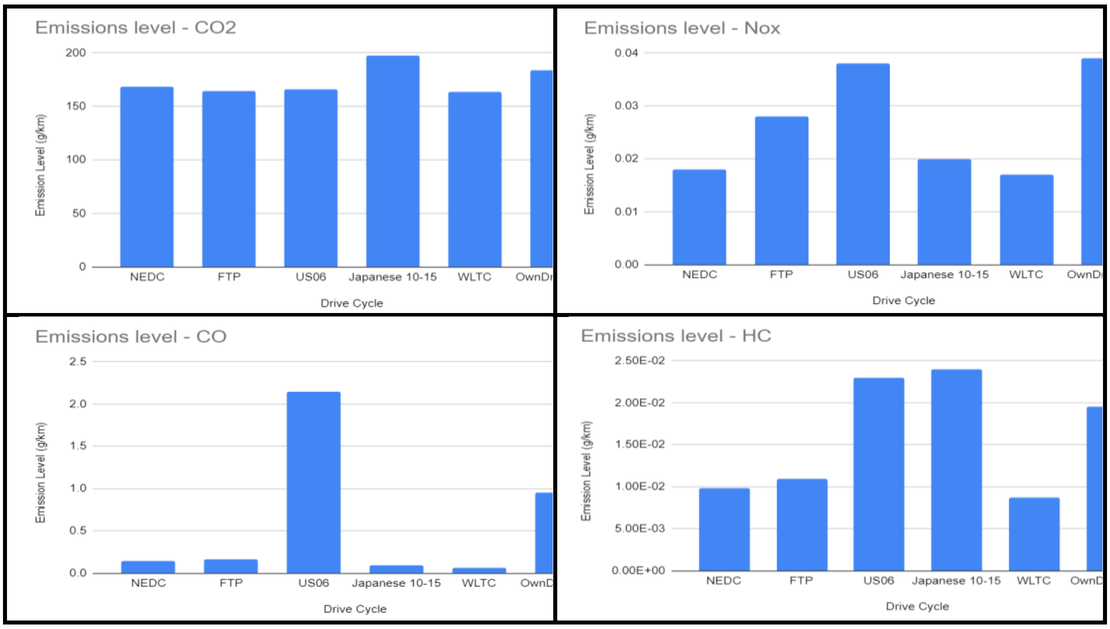

Figure 6 Comparison of emission results

Proposal for improvement

Improving fuel efficiency and reducing pollutant emissions are critical aspects of sustainable transportation. Based on the results and vehicles operating point it is evident that emission level cannot be controlled by single parameter. According to (Samuel, et al., 2004), speed and acceleration makes no difference if the vehicle operating points remain within optimal zone of the engine map. Considering that dynamics of driving behaviour and operating points on the engine map influence emission levels and fuel consumption, driving behaviours such as smooth acceleration, maintaining constant speed, avoiding frequent acceleration-deceleration, and gear shifting can be implemented to increase fuel efficiency and lower emission levels. Driving at the appropriate operating range, i.e. at high gear and lower RPM with a relatively higher load, will help improve fuel efficiency and should be prioritised to optimise performance.

Average Fuel Consumption; Part: Car-1	Total Emissions: Species 1; Part: Engine-1	Total Emissions: Species 2; Part: Engine-1	Total Emissions: Species 3; Part: Engine-1	Total Emissions: Species 4; Part: Engine-1
L/100 km	g	g	g	g
7.4694376	2691.637	0.63652694	15.187111	0.2579937

Table 5 Fuel economy and emission for own drive cycle with modified gear shift strategy

Own Drive Cycle	**Co2**	**NOx**	**Co**	**HC**	**L/100km**	**km/L**
	g/km	g/km	g/km	g/km		
Basic Gear Shift Strategy	184.1	0.039	0.95	0.0195	7.8	12.8
Modified Gear Shift Strategy	175.49	0.041	0.99	0.016	7.46	13.40

Table 6 Comparison of parameters for Real-world drive cycle with different gear shift strategy

Table5 includes the results for fuel economy and emission of real world drive cycle which was achieved with modified gear shift strategy with increased operating range for individual gear no. in order to avoid frequent gear change. This resulted in improved fuel economy and reduced emission for CO2 and HC species but increased emission of NOx and Co pollutants indicating the effects of engine loads, speed and other driving behaviour. Apart from driving strategy maintaining appropriate tyre pressure can also result in improved performance.

Summary

In this study, we estimated a model's fuel efficiency, emissions and validated them using experimental data. This validation allowed us to verify the simulation-based approach for estimating the performance of the vehicle for various parameters which is a more convenient and efficient technique in comparison to the traditional method. Further, the results obtained for fuel economy and emission values for varying drive cycles were compared enabling to identify the main factors affecting these performance. The study identifies that the fuel economy and emissions are primarily affected by parameters such as the engine operating range and driving behaviour. Further, this comparison enables to understand the difference in the results between legislative drive cycle and the real-world drive cycle, suggesting the importance of RDE for assessing the vehicle performance for day-to-day scenario. Additional suggestions for enhancing overall effectiveness in terms of fuel usage and emissions have been addressed.

Part 2

Introduction

The Hybrid electric vehicle (HEV) powertrain model refers to a vehicle with at least two power sources, it uses a combination of IC engine and electric motors to power the vehicle. The improved fuel economy and reduced emissions in comparison to the traditional IC engines are major highlight of the HEV's. Hybrid vehicles are majorly categorised into two types Mild Hybrid, Full hybrid which can be further be designed in series or parallel configurations. The main aim in the development of a Hybrid Electric vehicle is to improve the energy efficiency and emissions with extended range capability and provide a sustainable solution for transportation.

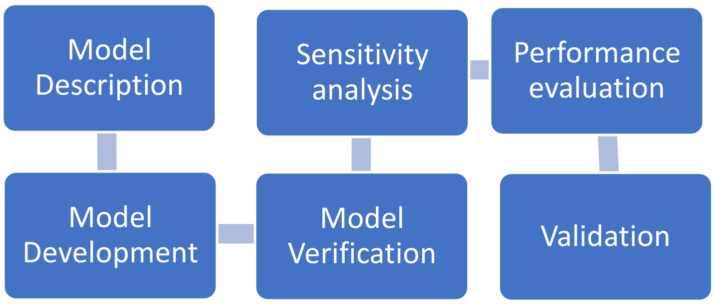

Figure 7 Systematic strategy to verify the integrity and validation of the model

Model

Description		Values
Vehicle Body	Mass of the vehicle	1334 Kg
	Frontal Area	2.57 m^2
	Co-efficient of Drag	0.25
	Tire Rolling Radius	310.45mm
	Wheelbase	2.7m
Engine	Engine Displacement	1.5 litre
	Fuel Rate Map	BSFC Map
	Total Airflow Map	Air flow map
	Emission Maps	CO2, CO, NOx & HC Map
Battery	Initial SOC	0.75 or 75%

Table 7 Toyota Prius Model Parameters

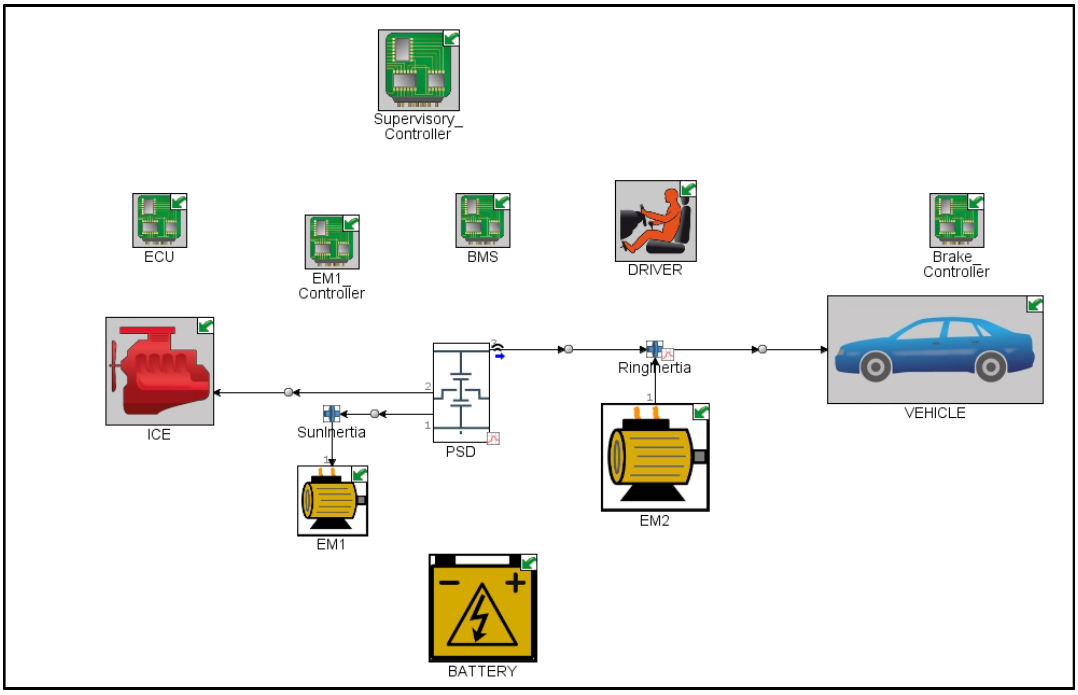

Figure 8 Model architecture

Major components of the system

- Engine
- Electric Motor
- Generator
- Power Split device
- Inverter
- Battery

Critical Components

- Brake Controller
- EM1 Controller
- Supervisory Controller
- BMS

Model Configuration and Description

The power-split HEV powertrain model consists of an IC engine, two electric motor and a planetary gear system to combine advantages of series and parallel configuration hybrid vehicle. The model is designed such that the engines shaft is connected to planet carrier(input), the generator is connected to the sun(input) and the motor is connected to the ring gear(output). Additionally the ring gear is also connected to the wheels through the driveline. This design enables the engine to power the wheels and also to operate the generator simultaneously. The generated electricity is further is used for either charging the battery or extending the battery power to the drive electric motor or both. The speed of the engine, generator and the motor are correlated, wherein the engine speed and generator is dependent on the vehicle speed. This model does not require external charging. (Staunton , et al., 2006)

Control Logic

- Based on the tractive power demand from the vehicle, the additional power is provided using the electric motor depending on the SOC of the battery for the HEV assist state.
- Under normal operating conditions, the power generated from engine is used for both, driving the generator and the vehicle.
- During deceleration and braking depending on the SOC, the motor is used as generator for regeneration of electricity by recovering the kinetic energy.
- During idle conditions and when the engine is operated outside the set speed range the engine is automatically turned off.

Since there weren't sufficient data to estimate the emission values, the emission results for the model were estimated using the emissions maps of comparable Euro IV vehicle model since the similar specification engine with similar technology tend to have similar emission profiles. But it is also important to consider that the obtained result is just an estimate and not accurate.

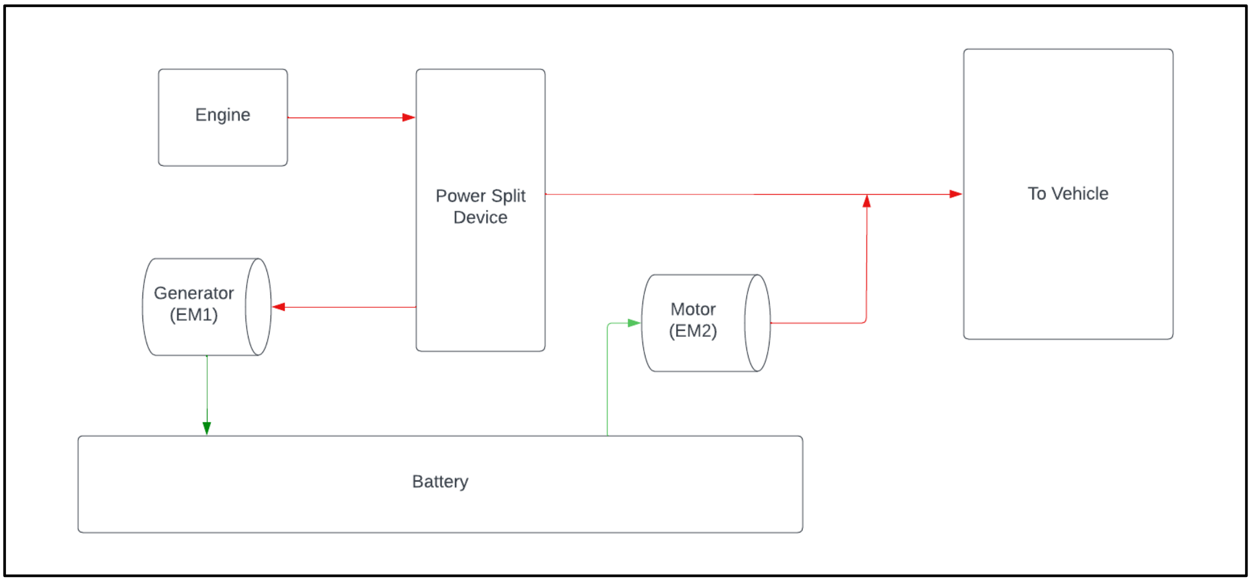

Figure 9 Flowchart suggesting the power flow in Prius model

Braking Condition	Operating Condition	Type of Braking Used	
		Regeneration Braking	Friction Braking
No Brake Demand	Tractive torque demand > 0 Nm	No	No
Braking - No Regen	If SOC>0.7 & Acceleration<-5m/s^2	No	Yes
Regen Braking - Under Limit	If SOC<0.7 & Tractive power demand < 0Nm & < regen limit	Yes	No
Regen Braking - Over Limit	If SOC<0.7 & Tractive power demand > regen limit	Yes	Yes

Table 8 Brake Controller Operating conditions

Validation

The model was validated for the fuel consumption parameter for NEDC values obtained using VCA Datasheet.

Parameter	Experimental Test Data (for NEDC)	Simulation Test Data (for NEDC)
Fuel Consumption (L/100 km)	4.3	4.258

Table 9 Comparison of simulation and experimental test results for validation of model

Results and discussion

The developed HEV model was simulated for NEDC and Real-world Drive cycle. The obtained results are compared.

Part B - Drivecycle Result Comparison

	Unit	NEDC	Owndrivecycle
Total Distance Traveled	m	11044.693	15570.412
Average Gas Mileage	km/L	23.4801206325	15.05305119528
Average Fuel Consumption	L/100 km	4.258934	6.6431904
Total Emissions: Species 1	g	1363.4119	3008.5273
Total Emissions: Species 2	g	5.7339306	7.2373934
Total Emissions: Species 3	g	0.090411134	0.1894489
Total Emissions: Species 4	g	2.4286432	6.122153

Figure 10 Comparison of Pollutant emission and fuel consumption for drive cycle.

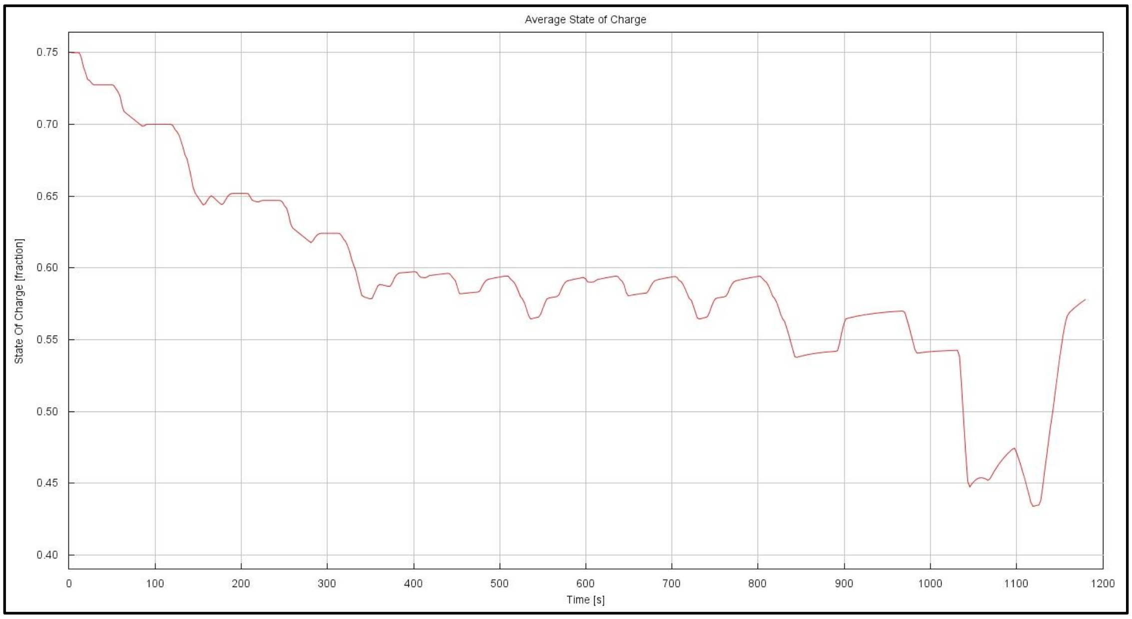

Figure 11 Average SOC of Battery during NEDC

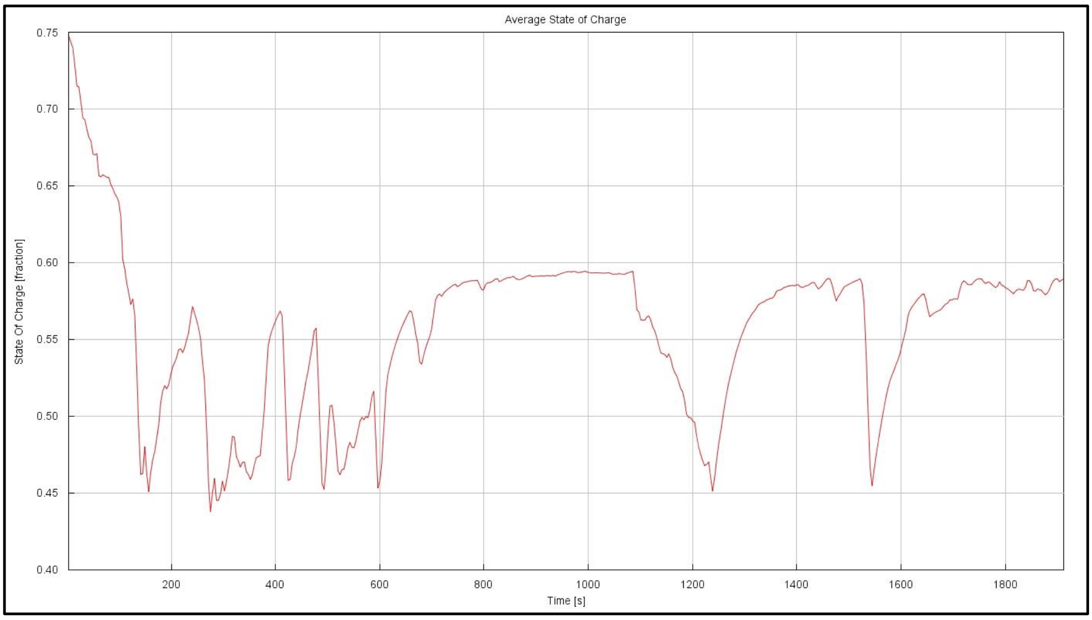

Figure 12 Average SOC of Battery for own drive cycle

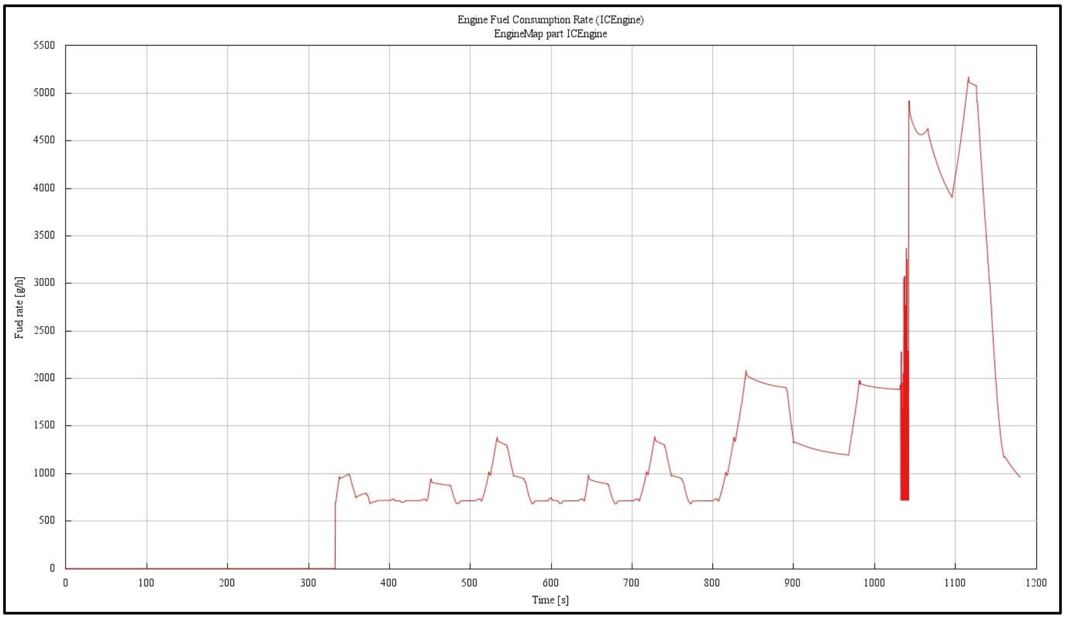

Figure 13 Engine fuel consumption for NEDC

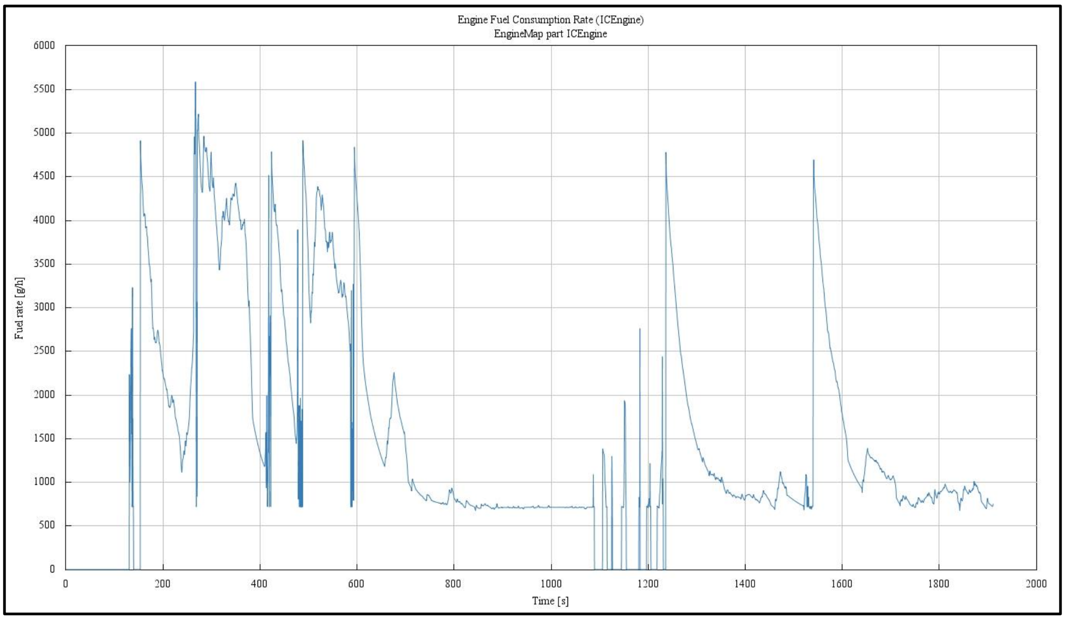

Figure 14 Engine fuel consumption for Real-world drive cycle

To determine the performance and investigate the efficiency, the developed vehicle model was tested for a legislative(NEDC) and real-world drive cycle. Due to aggressive driving behaviour in the real-world drive cycle, a varying behaviour in SOC was observed. Considering the defined control strategy for charging the battery and use of the electric motor for operation resulted in frequent charging and discharging of the battery. In comparison of the two drive cycle, for NEDC the required influence of engine was on the lower side with the vehicle majorly operating on the EV mode resulting in better fuel economy. The control strategy of model has major role in determining the operating mode and increasing the overall efficiency.

Summary

In this study, we have discussed the powertrain model configuration and the control strategy (operating condition) of the Toyota Prius model, which are the main highlight behind the increased efficiency in terms of fuel economy and pollutant emission of the HEV model. The model architecture enabling to use the combined power source with a planned and efficient control strategy for varying operating conditions to achieve high fuel economy. The vehicle performance can be further improved by using optimal control strategy.

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